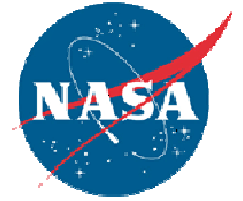


# **A Fully Non-Metallic Gas Turbine Engine Enabled by Additive Manufacturing**

Joseph E. Grady  
NASA Glenn Research Center

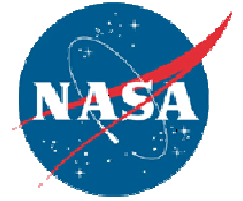
for the 39<sup>th</sup> International Conference and Exposition on  
Advanced Ceramics and Composites

Daytona Beach, Florida  
January 25–30, 2015



# Outline

- Project Description
- Development of additive manufacturing for turbine engine composites
- Component Applications
- Engine System Benefits
- Technology Maturity
- Next Steps



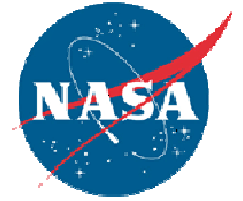
# Project Innovation & Approach

## **Innovation:**

Conducted the first comprehensive evaluation of emerging materials and manufacturing technologies that will enable fully non-metallic gas turbine engines for reduced aircraft emissions, fuel burn and noise.

## **Approach:**

- Assess the feasibility of using additive manufacturing technologies to fabricate gas turbine engine components from polymer and ceramic matrix composites.
- Fabricate and test prototype components in engine operating conditions
- Conduct engine system studies to estimate the benefits of a fully non-metallic gas turbine engine design in terms of reduced emissions, fuel burn and cost



# Accomplishments

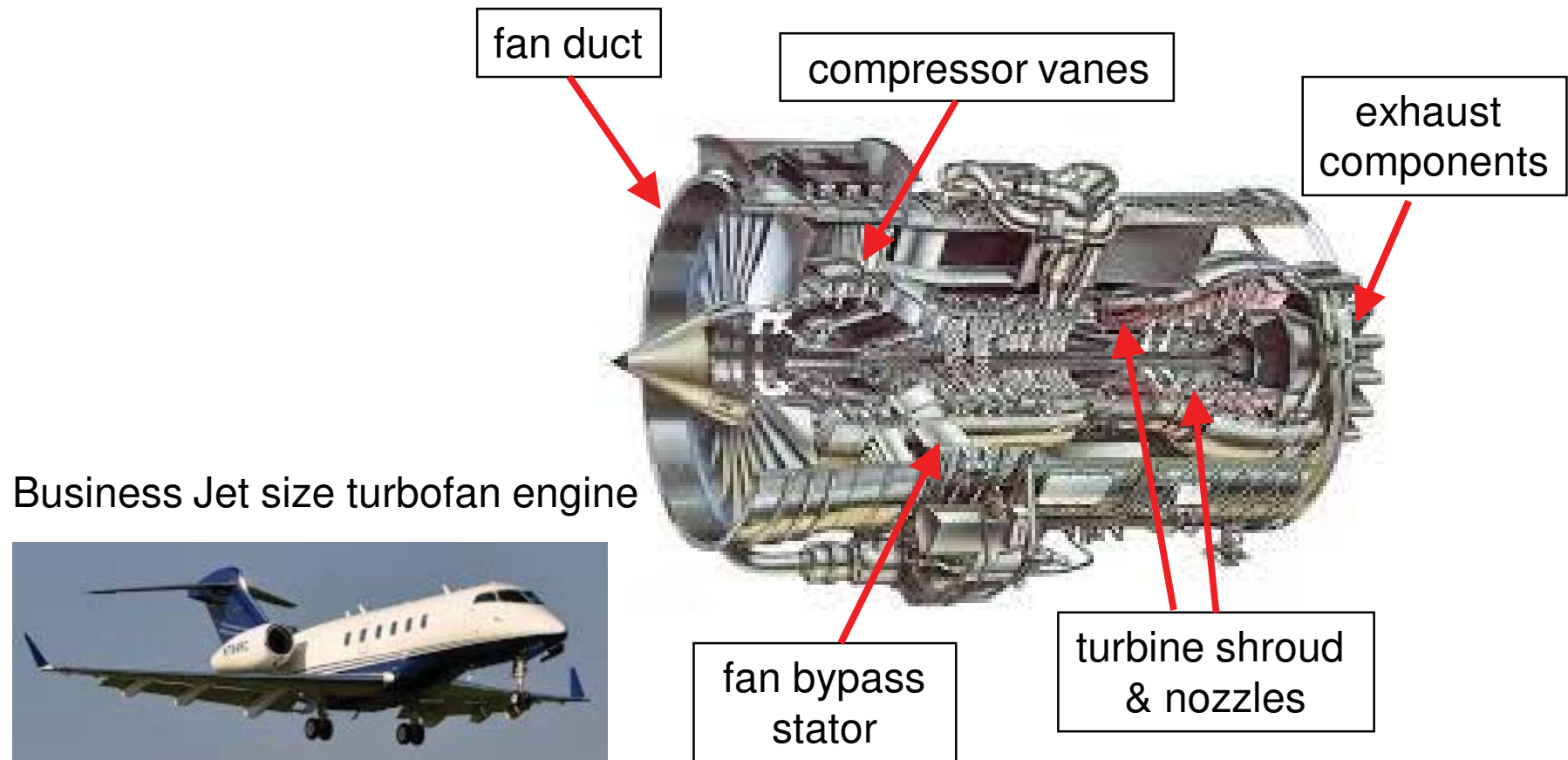
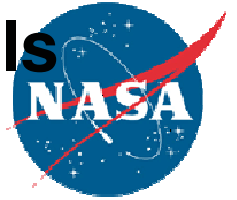
- First to use additive manufacturing processes to fabricate turbine engine components from Ceramic Matrix Composites and Polymer Matrix Composites
- Demonstrated advanced structural concepts enabled by additive manufacturing technologies
- Estimated the reduction of engine emissions and fuel burn due to these materials and fabrication processes
- Determined the maturity of additive manufacturing technologies for fabrication of composite turbine engine components

# Project Team

- **RP+M** (Additive Manufacturing): Tom Santelle, Clark Patterson
- **Honeywell Aerospace** (Engine Systems & Components):
  - Mike Vinup, Natalie Wali, Don Weir
- **Ohio Aerospace Institute**
  - Ceramic Processing: Mrityunjay Singh
  - Polymer characterization: Eugene Shin
- **NASA Glenn Research Center**
  - Engine Systems Analysis: Bill Haller, Sydney Schnulo, Bob Plencner
  - Materials Characterization: Kathy Chuang, Mike Halbig, Bob Draper
  - Component Rig Testing: Phil Poinsatte, Doug Thurman
- **NASA Langley Research Center** (Acoustic testing): Mike Jones
- **NASA Aeronautics Academy Students:** Chao Lao (Cal Poly), Jeremy Mehl (Princeton), Morgan Rhein (Purdue)



# Lightweight, high temperature composite materials improve engine efficiency

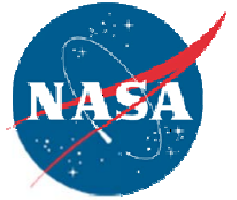


Business Jet size turbofan engine



Use of these materials & manufacturing technologies in critical components will reduce emissions (8%), fuel burn (5%), engine weight (15%) for business jet size engines

# Additive Manufacturing of Composite Materials



## Conventional Manufacturing

- Customized parts in small volumes are time consuming and expensive to produce.
- Complex shape fabrication issues: mold design, dimensional tolerances, etc..
- Manufacturing of multifunctional parts are challenging.

## Additive Manufacturing

- Small series of ceramic parts can be manufactured rapidly and cost-effectively.
- Specific molds are not required.
- Different designs can be optimized (no major cost of changes)
- Parts with significant geometric complexity.

## Material and Process Challenges

- Property and behavior of starting materials
- Sintering and densification challenges
- Process modeling
- Mechanical behavior
- NDE and in-situ damage characterization
- Material and property databases

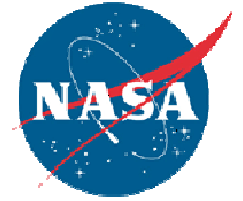
Efforts in the last >30 years have now resulted in commercialized turbine engine applications.

Efforts in this very promising field are just now underway.

Materials and processing challenges are quite similar

***Largest barrier to CMC insertion has been high acquisition cost***

***For AM, the starting materials are very low cost (powders and fibers).***

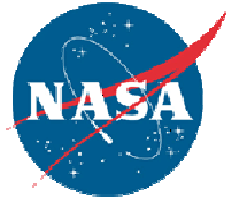


# Polymer Matrix Composites

- Fabrication Process
- Material Characterization
- Component Demonstrations



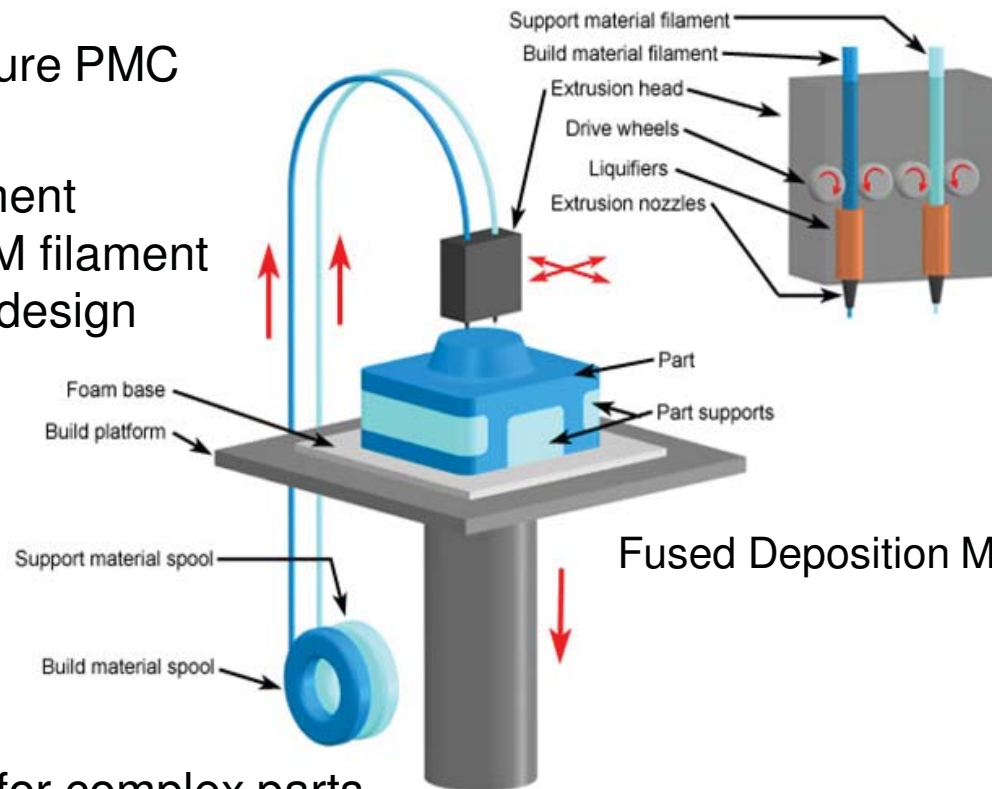
# Fused Deposition Modeling for Polymer Matrix Composites



*Melts polymer filament and deposits it layer-by-layer following CAD files*

Fabrication of high temperature PMC was enable by:

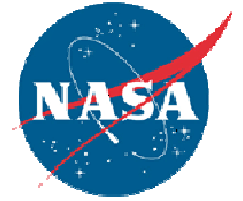
- Chopped-fiber reinforcement
- Moisture reduction in FDM filament
- Versatile printing pattern design



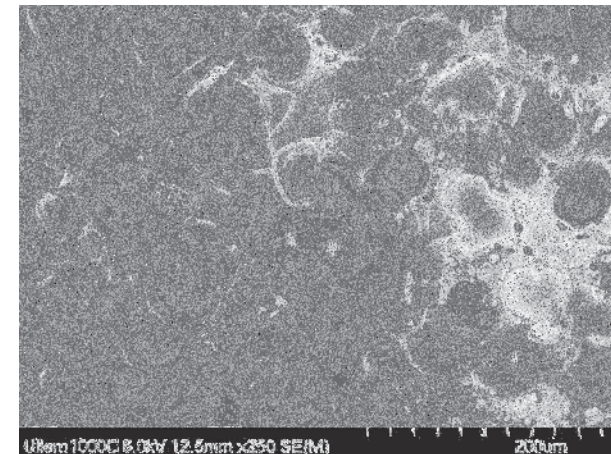
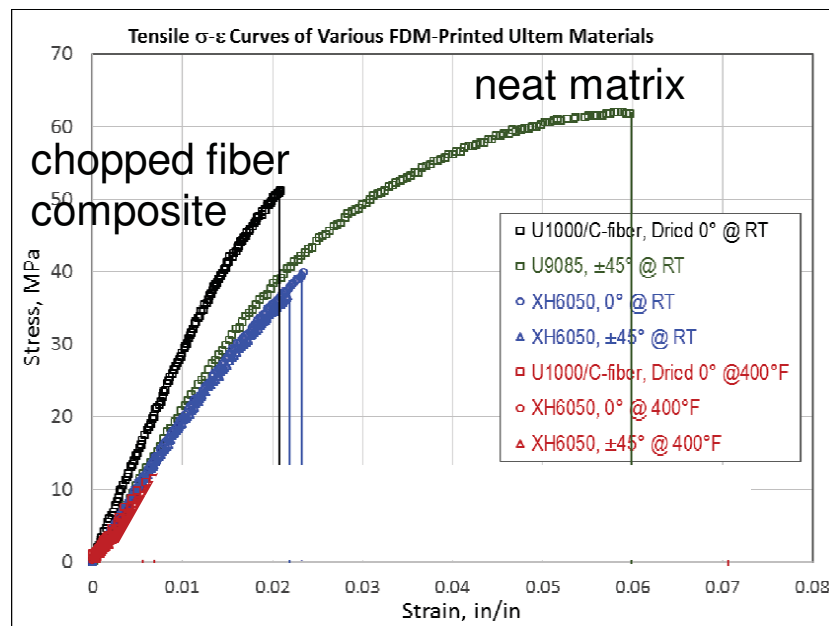
Fused Deposition Modeling

Benefits:

- Quick turn around time for complex parts
- Shorter component production and testing cycle
- Reduced cost of low production volume components

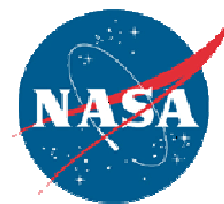


# Fiber reinforcement increases modulus of high temperature polymers

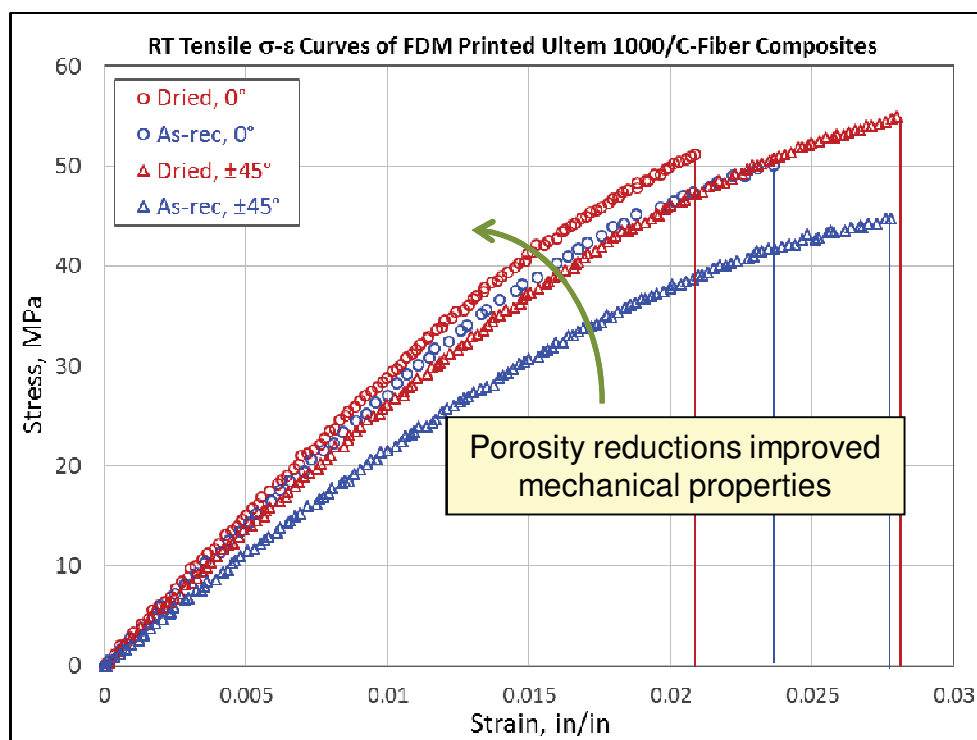


fibers are visible in composite fracture surface

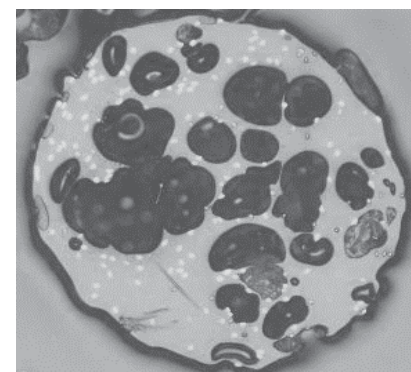
Addition of 10% chopped fiber (AS4) increased modulus 40%



# Processing approach was refined to optimize properties of high temperature polymer composites



Reduction of moisture content in FDM polymer filament resulted in lower porosity and improved composite properties



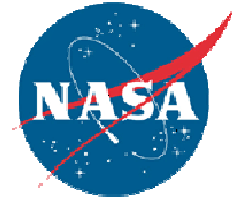
Initial composites were porous



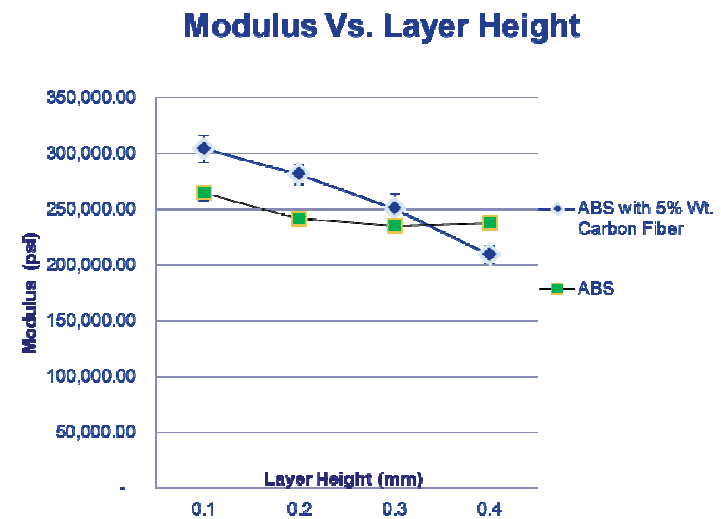
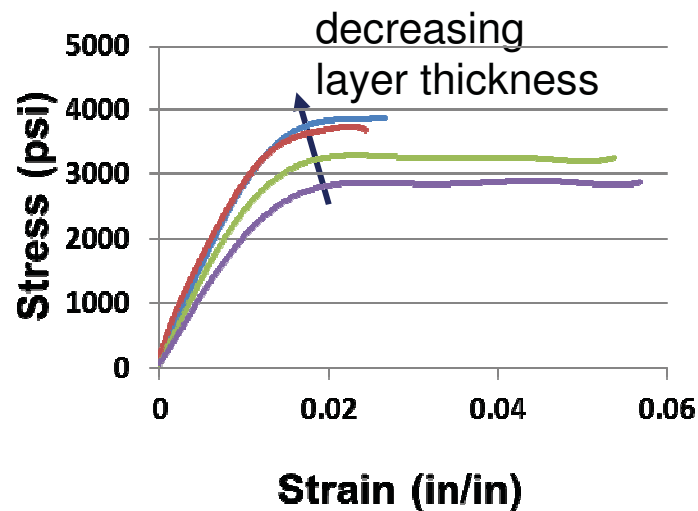
Process improvement reduced porosity 20%

27% modulus increase and 20% strength increase measured for +/- 45° composites

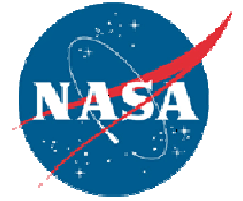
# Additional process improvements identified for improving PMC properties



Further reduction of porosity is needed for structural components



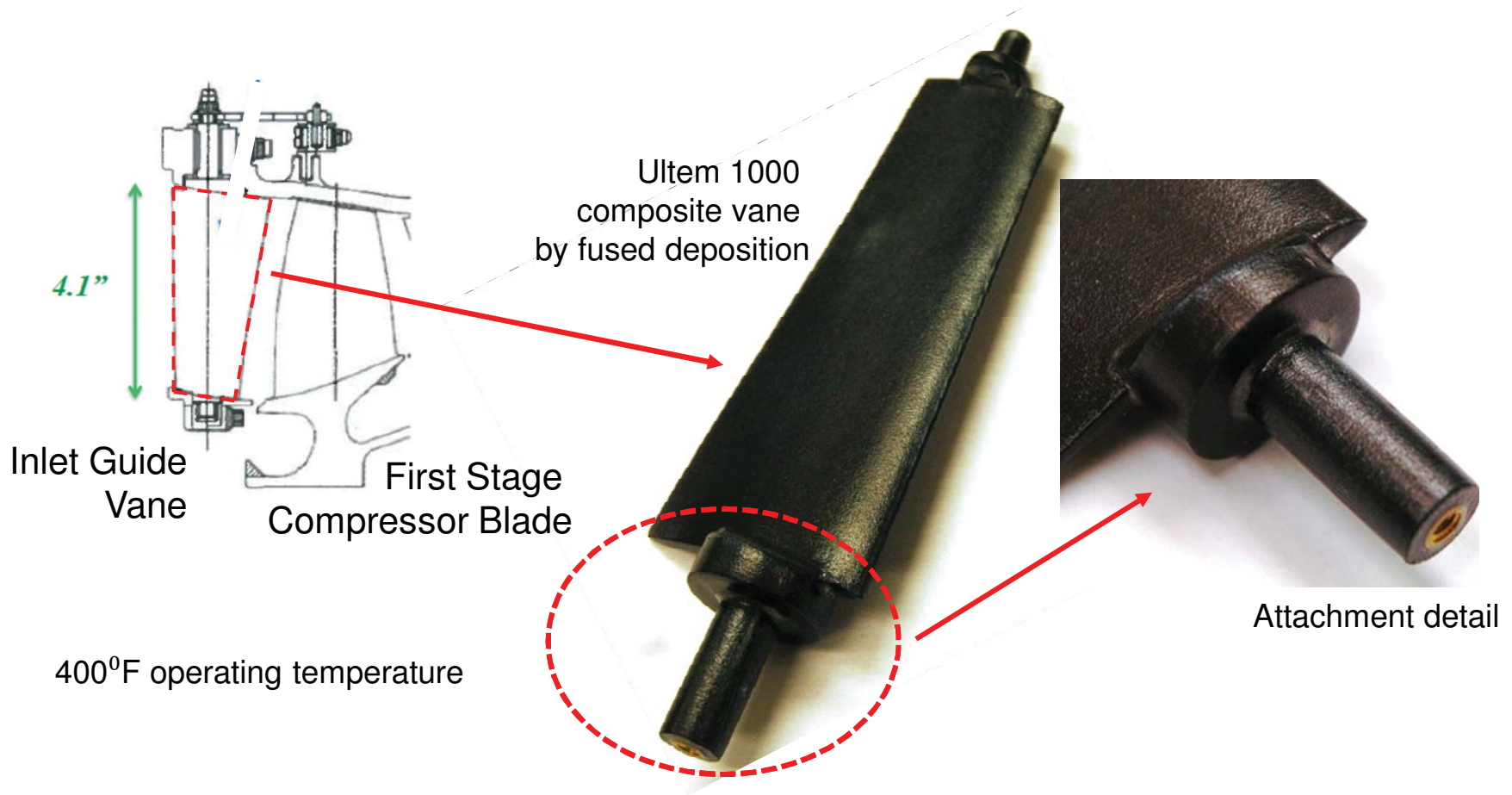
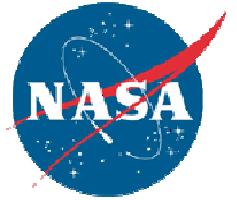
- Experience with ABS composites shows strength and modulus can be increased by reducing layer thickness during FDM process
- Optimization of processing temperature & speed will also improve properties



# PMC Component Applications

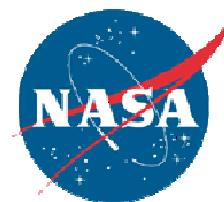
- Compressor Guide Vane
- Acoustic Liner

# Fabricated Compressor Inlet Guide Vanes with High Temperature Polymer Matrix Composites

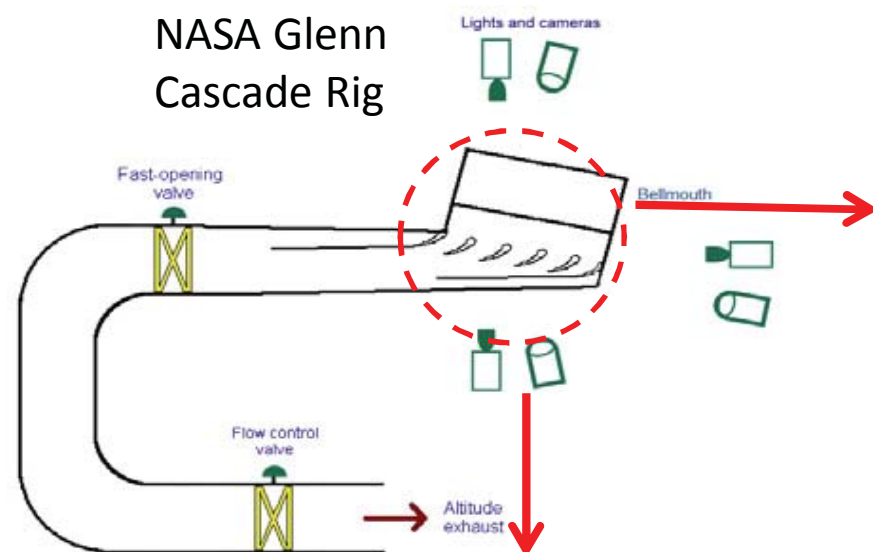


- Ultem 1000 ( $T_g = 423^\circ\text{F}$ ) with chopped carbon fiber
- First Polyetherimide composite fabricated

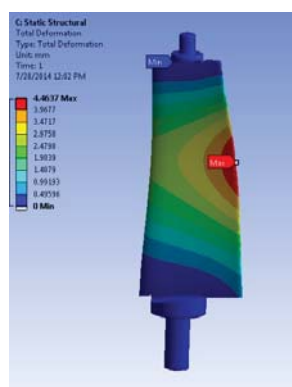




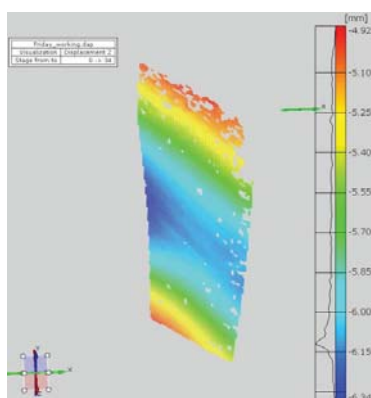
# Structural integrity of inlet guide vane was evaluated under aerodynamic loading



**Vane Configuration in Cascade Rig**



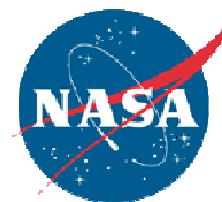
**Stress Analysis**



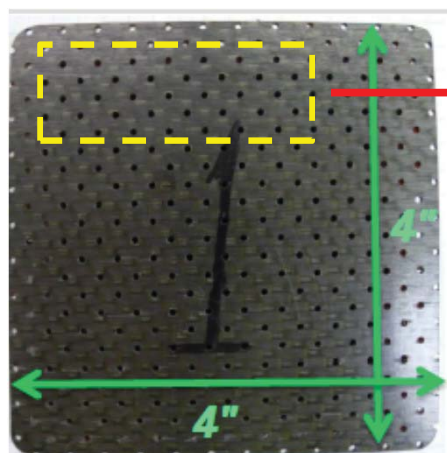
**Deformation Measurements**

Other FDM composites being evaluated:

Matrix (+C fiber)	Use Temperature (°F)
Ultem 1000	350
Ultem 9085	275
ABS	200



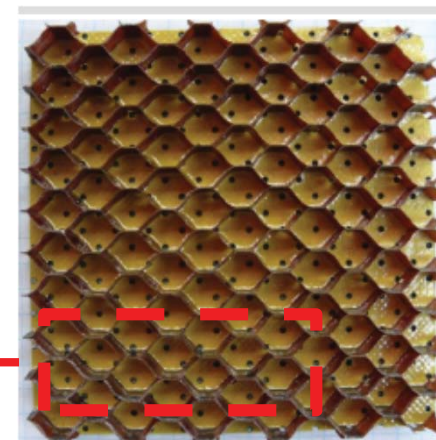
# Fused Deposition Modeling Simplifies Acoustic Liner Fabrication



Perforated Facesheet

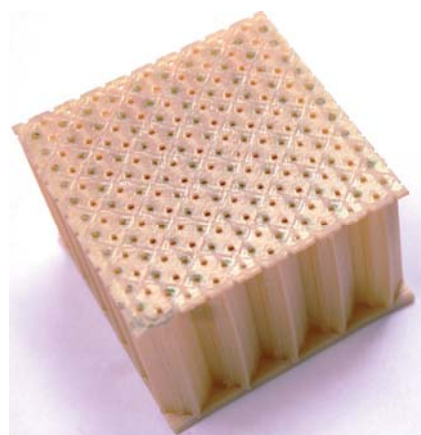


Bonded Structure



Honeycomb

Current manufacturing approach requires metal forming, bonding and drilling

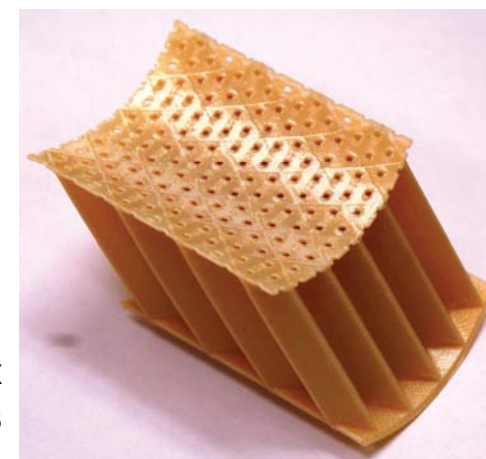


standard liner configuration

integral facesheet/honeycomb structure is fabricated in one step using Fused Deposition Modeling

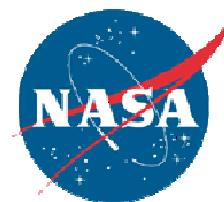
200°F operating temperature

complex geometries

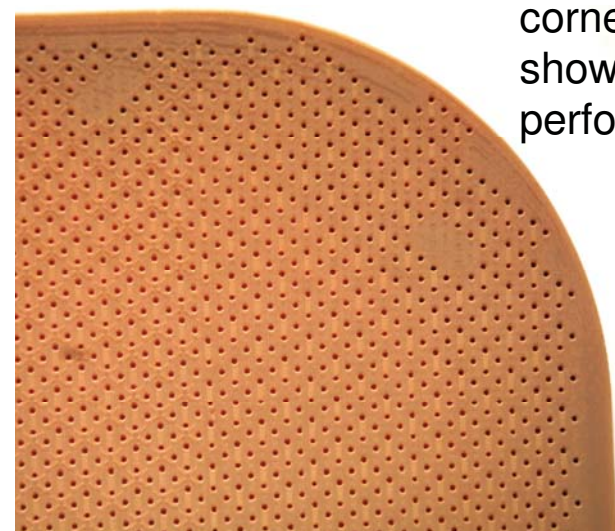
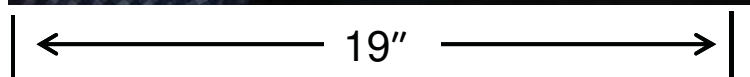


Fabricated with monolithic Ultem 9085 thermoplastic ( $T_g = 367^\circ\text{F}$ )



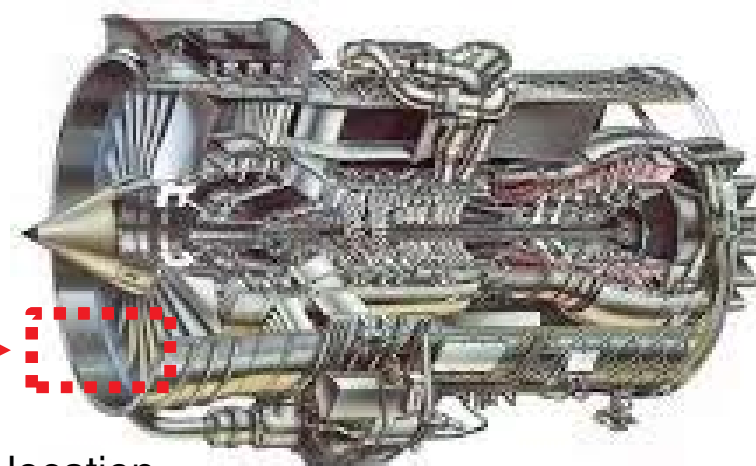
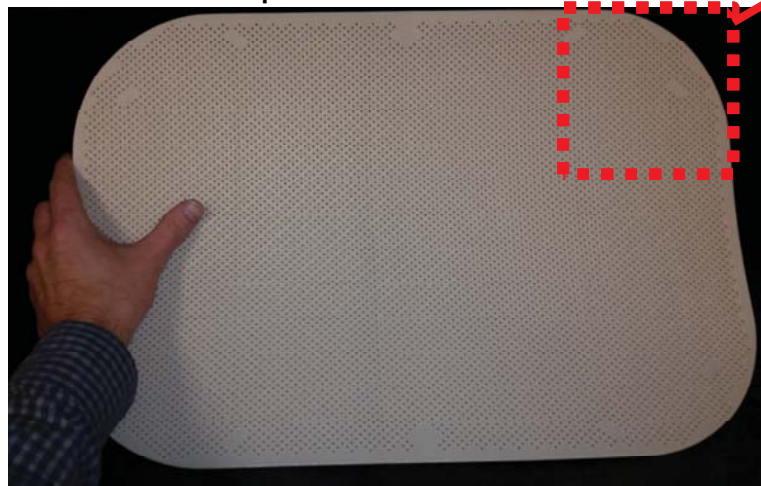


# Fabrication of full-scale engine access panel demonstrated

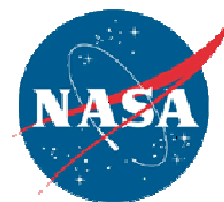


corner detail  
shows acoustic  
perforations

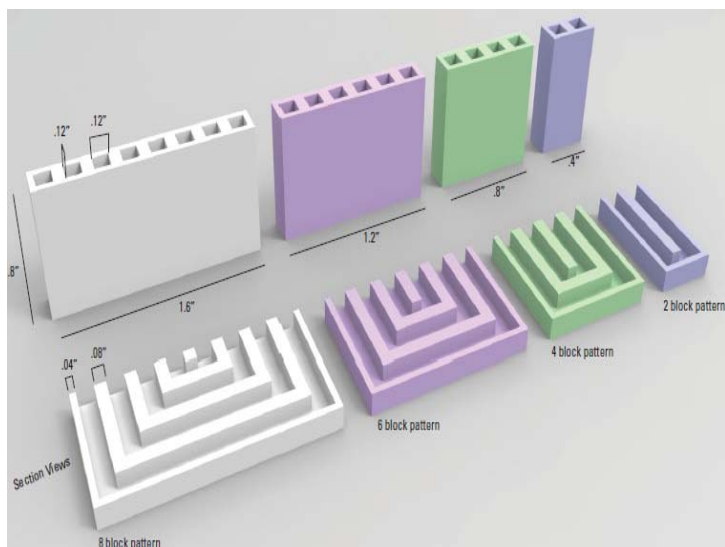
inner surface incorporates acoustic treatment



panel location



# Fused Deposition Modeling enables fabrication of advanced acoustic liner concepts

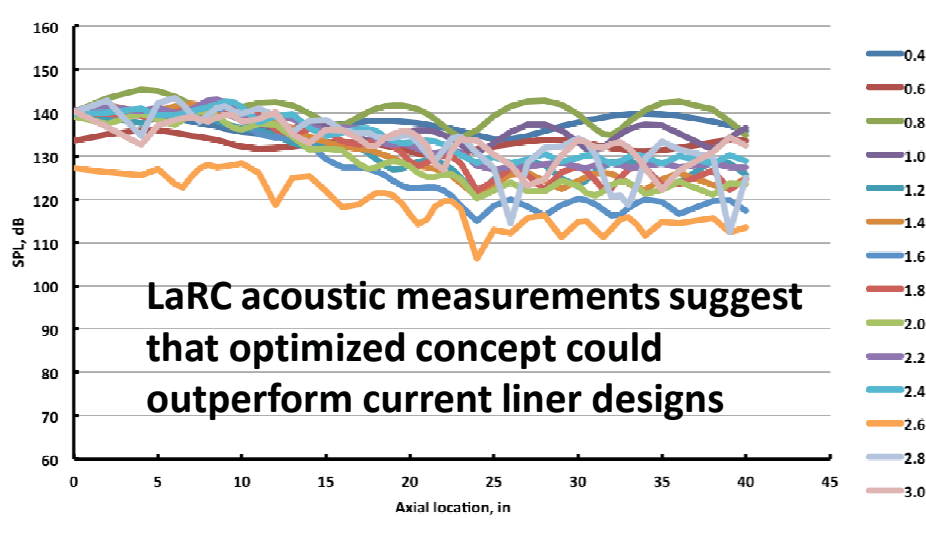
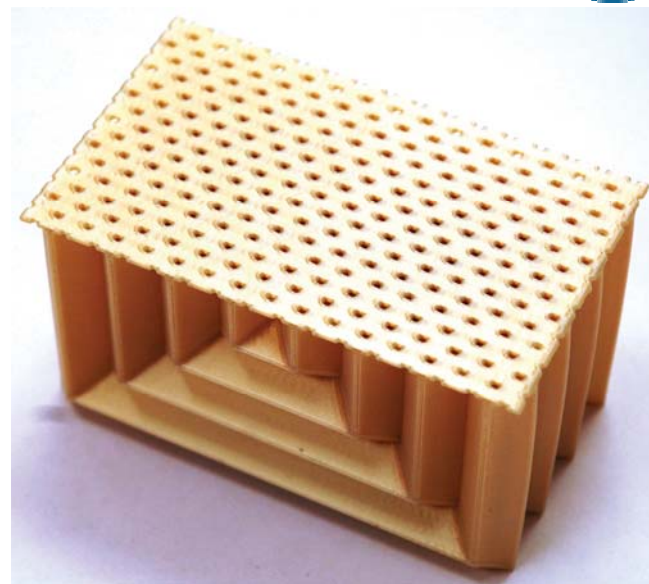


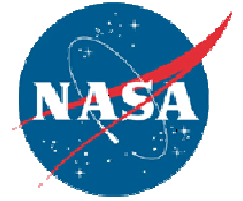
**Acoustically-tuned passages provide broadband noise attenuation**



**Fabricated 16x2 inch test article**

**FDM sample of advanced liner**

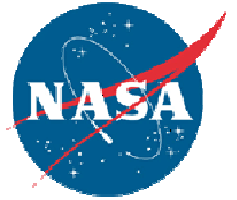




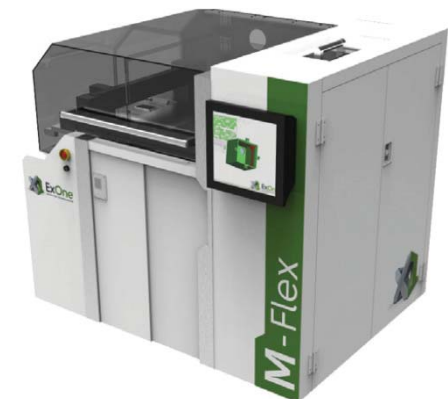
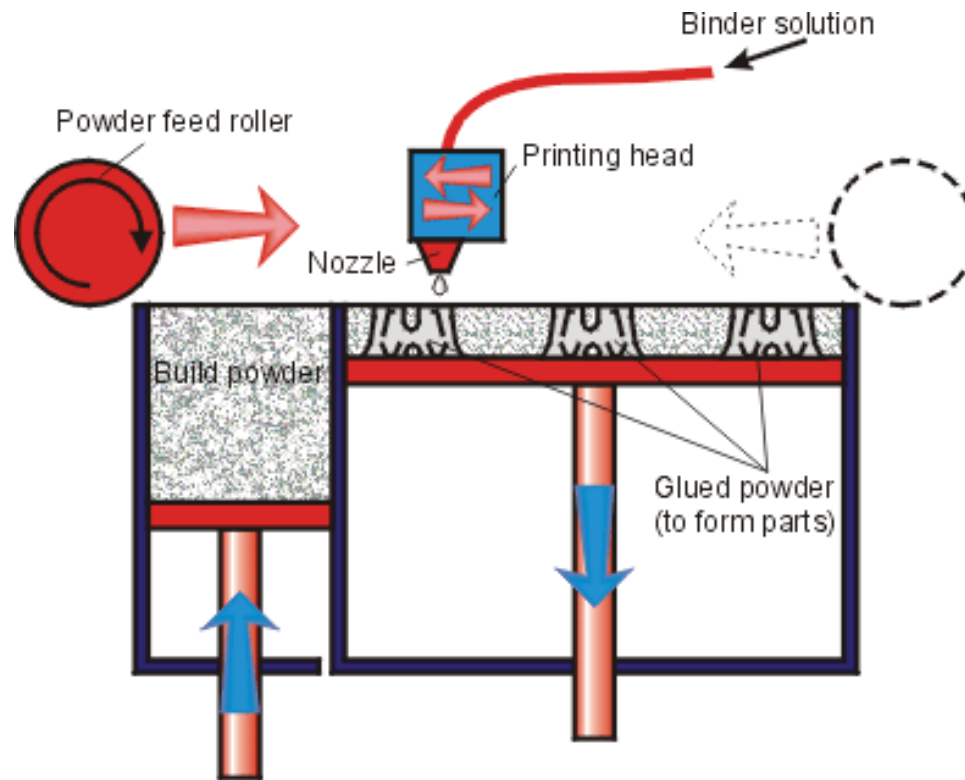
# Ceramic Matrix Composites

- Fabrication Process
- Material Characterization
- Component Demonstration

# Binder Jet process was adapted for fabricating Ceramic Matrix Composites



*An inkjet-like printing head moves across a bed of ceramic powder depositing a liquid binding material in the shape of the object's cross section*

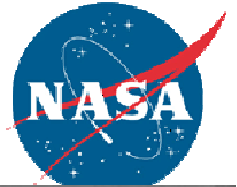


ExOne's M-Flex print machine

Binder jet printing allows for powder bed processing with *tailored binders* and *chopped fiber reinforcements* for fabricating advanced ceramics



# Powder composition is key to Binder Jet processing for structural ceramics and composites



*optimization of powder spreading and bimodal distribution of powders is critical*

## Constituents

- **SiC powders:** Carborex 220, 240, 360, and 600 powders (median grain sizes of 53, 45, 23, and 9 microns)
- **Infiltrants:** SMP-10 (polycarbosilane), SMP-10 w/ SiC powder, phenolic (C, Si, SiC powder loaded), pure silicon
- **Fiber reinforcement:** SiC chopped fiber; 7 micron mean dia, 65-70 micron mean length, 350 GPa Modulus

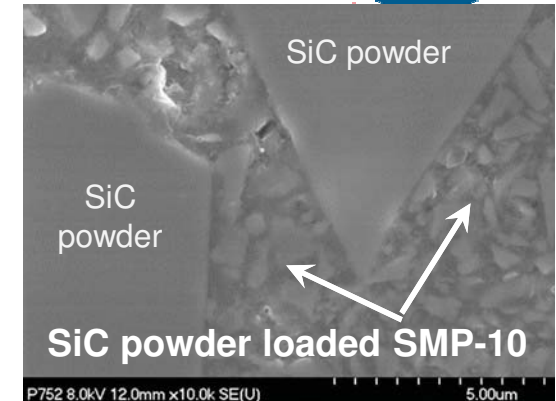
## Microstructure

- Optical microscopy
- Scanning electron microscopy

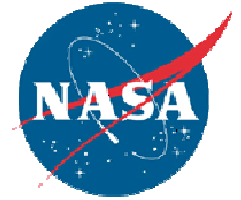
## Properties

- Material density (as-manufactured and after infiltration)
- Mechanical properties

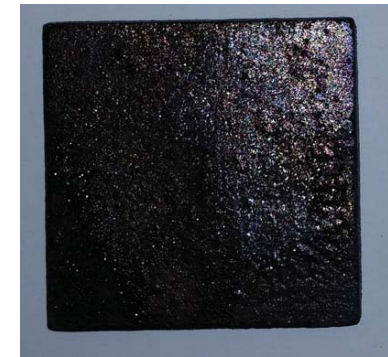
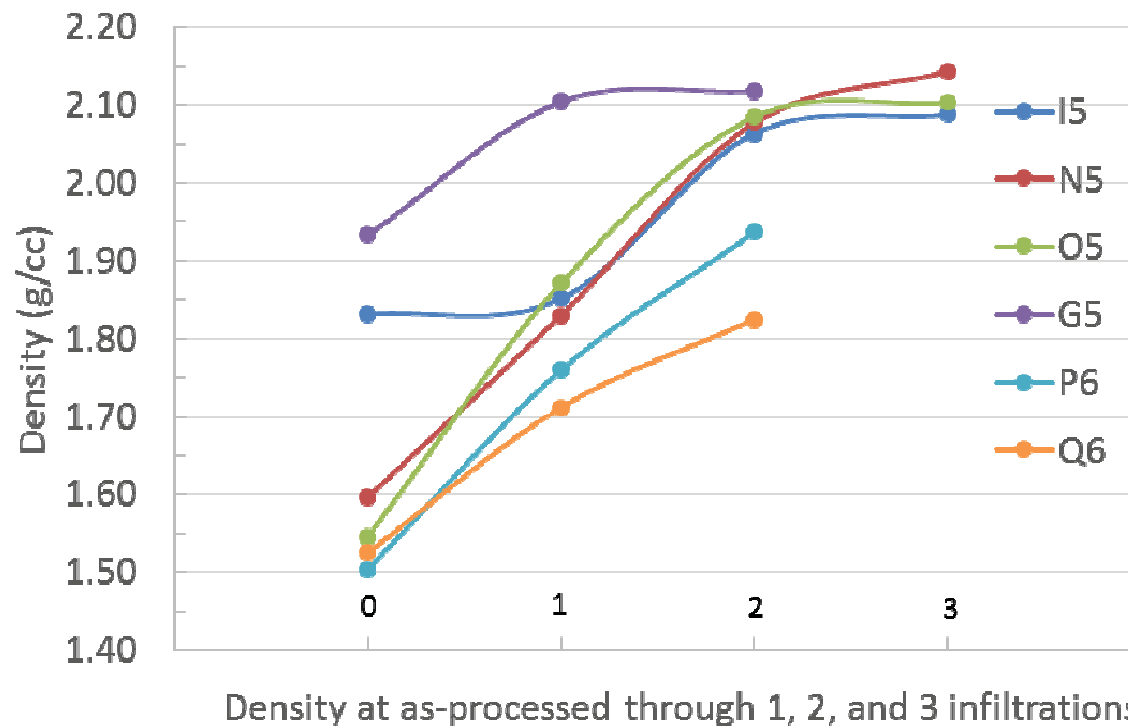
**Processing, microstructure, and property correlations provide an iterative process for optimizing CMC materials**



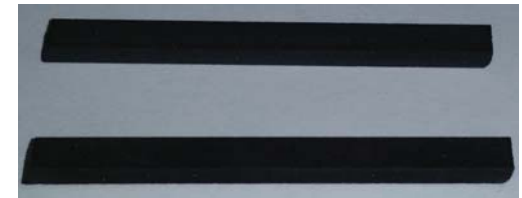
# Optimization of Binder Jet process for ceramics



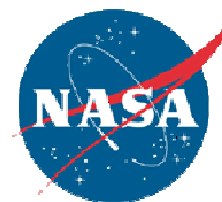
*multiple infiltrations with SiC powder-loaded polymers  
increase material density*



Panels and test coupons  
fabricated for mechanical  
property measurements

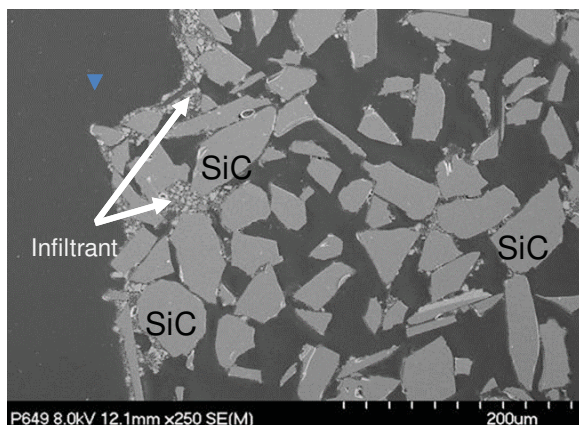


Infiltrations increased density 30%  
by optimizing composition of ceramic powders used

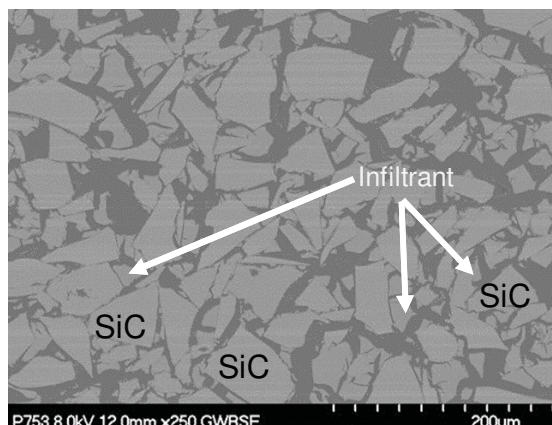


# Fabrication of chopped fiber CMC by Binder Jet + polymer infiltration

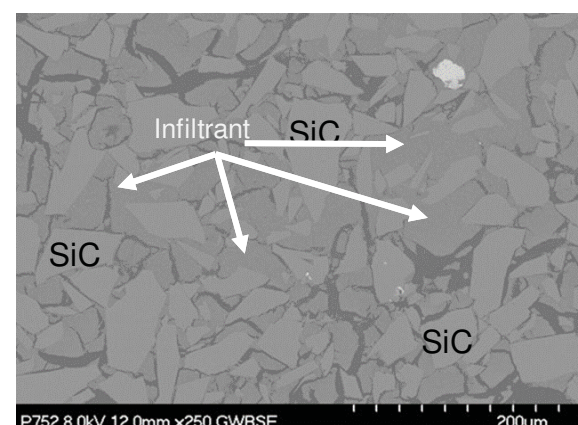
1. Densify SiC matrix with successive infiltrations 



First iteration shows loose particle packing and limited infiltration

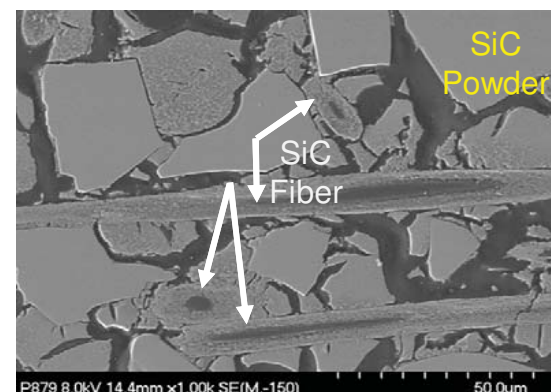
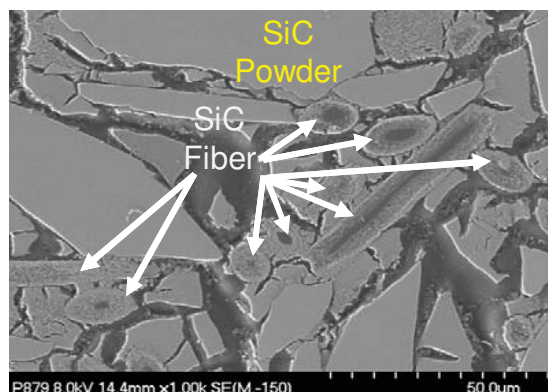


Blending two powder sizes improves packing and infiltration



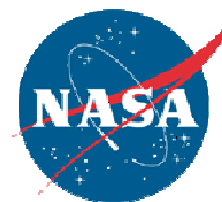
Loading infiltrant with smaller dia powders further improves density

2. Add chopped fiber to Binder Jet powder bed



CMC with 35 vol% SiC fiber loading (1000x magnification)

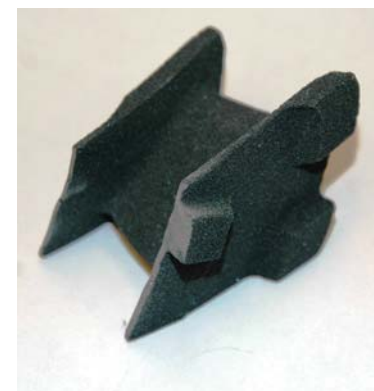
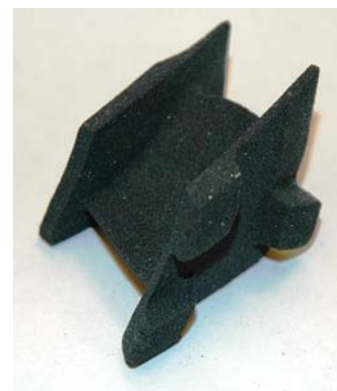




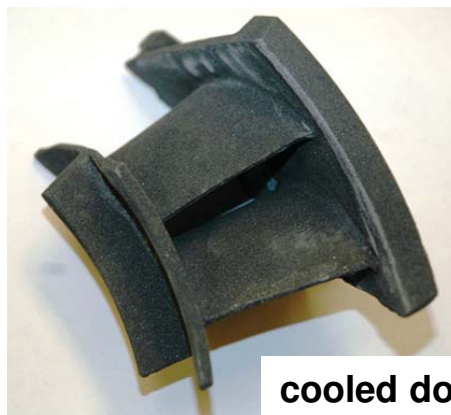
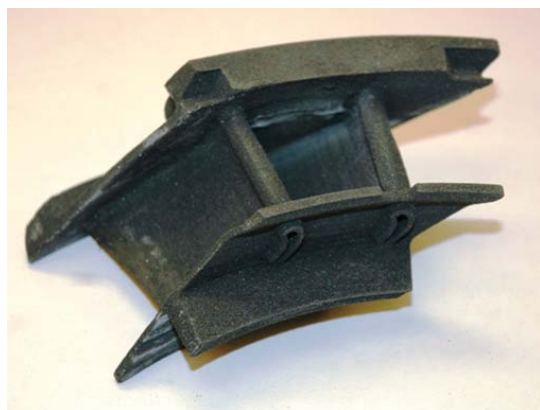
# The first CMC turbine engine components by additive manufacturing



high pressure turbine nozzle segments



first stage nozzle segments

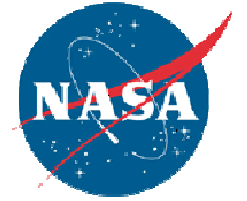


cooled doublet nozzle sections



**SiC/SiC CMCs have 20% chopped SiC fiber**

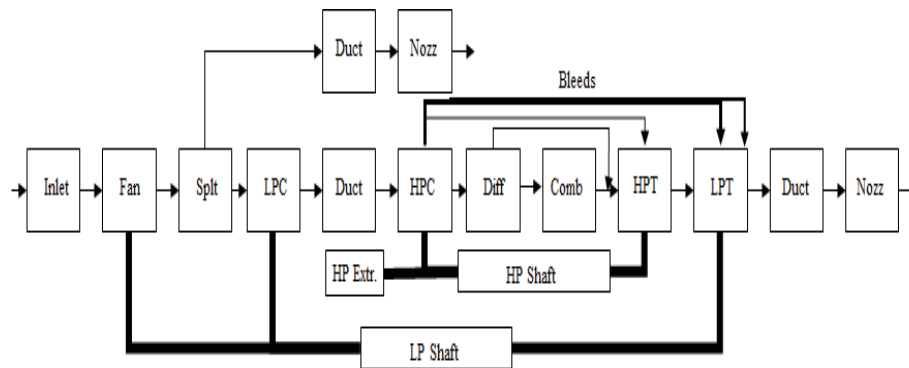
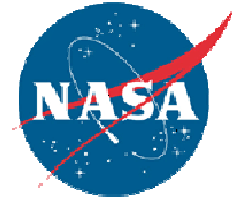




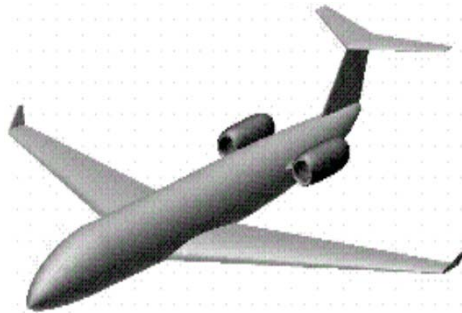
# Impact on Engine Systems

- Weight Reduction
- Fuel Burn Reduction
- Emissions Reduction
- Noise Reduction
- Structural Design Optimization

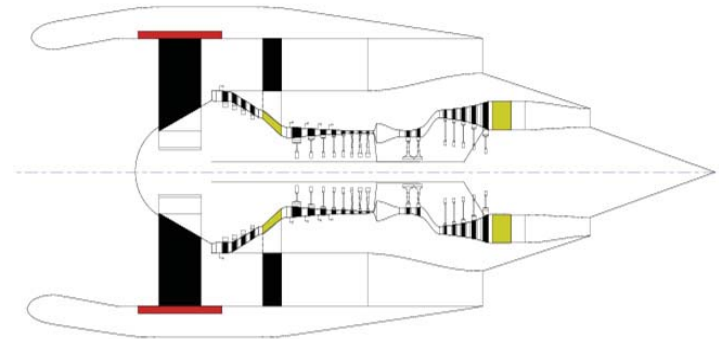
# Engine systems analysis & modeling tools were used assess impact of advanced technologies



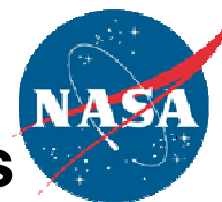
**Model Propulsion system performance impacts (using NPSS)**



**Quantify fuel burn impacts on aircraft (using FLOPS)**

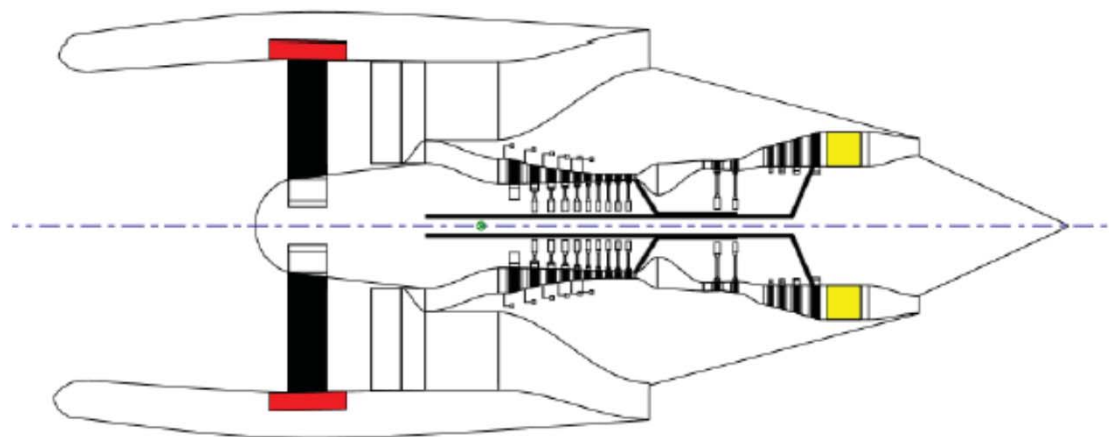


**Model Propulsion system weight impacts (using WATE)**



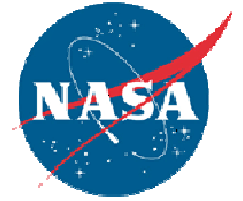
## Impact:

**Advanced materials & manufacturing technologies would reduce engine weight by 15%**



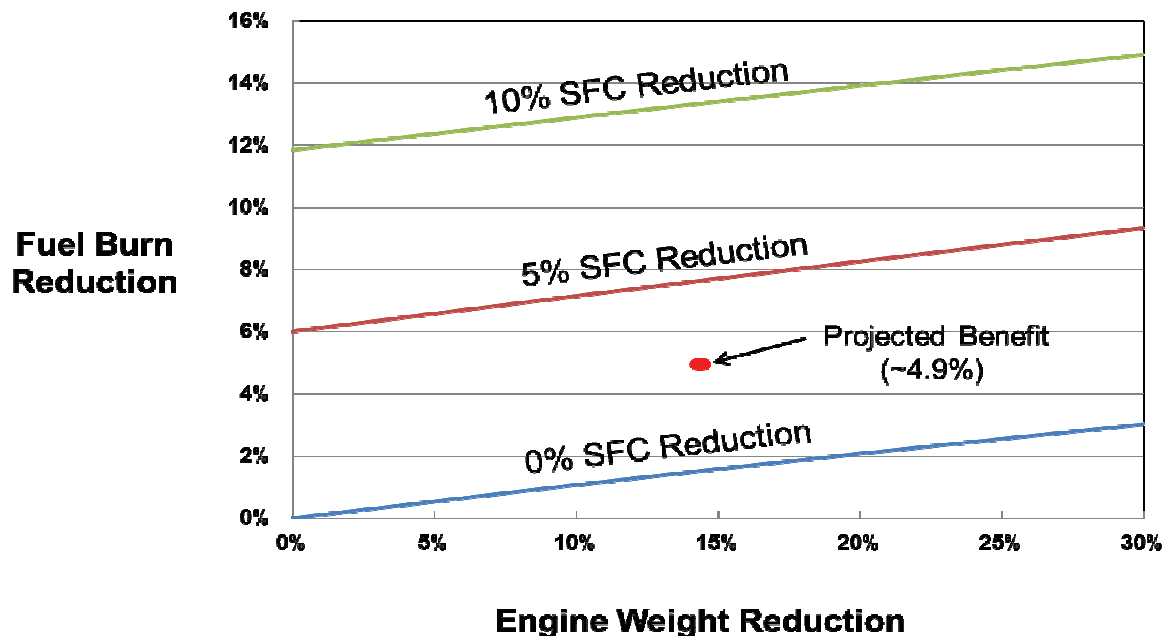
Weights (lbs)		Dimensions (inches)	
Bare Engine Wt.	2075	Engine Length	91.5
Accessories Wt.	635	Engine Pod C. G.	28.3
Engine Wt.	2710	Fan Diameter	48.1
Inlet/Nacelle Wt.	505	Nacelle Max. Diameter	63.1
Total Pod Wt.	3215	Total Pod Length	125.5

~14.5% Reduction  
vs. Baseline

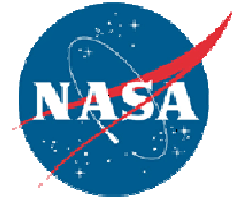


## Impact:

**Advanced materials & manufacturing technologies would reduce fuel burn by 5% and emissions by 8% for Regional Jets**



Fuel Burn Sensitivities for baseline Regional Jet show **4.9% reduction in aircraft fuel burn** and a corresponding **8.3% reduction in NOx Emissions** due to the use of advanced materials and manufacturing processes

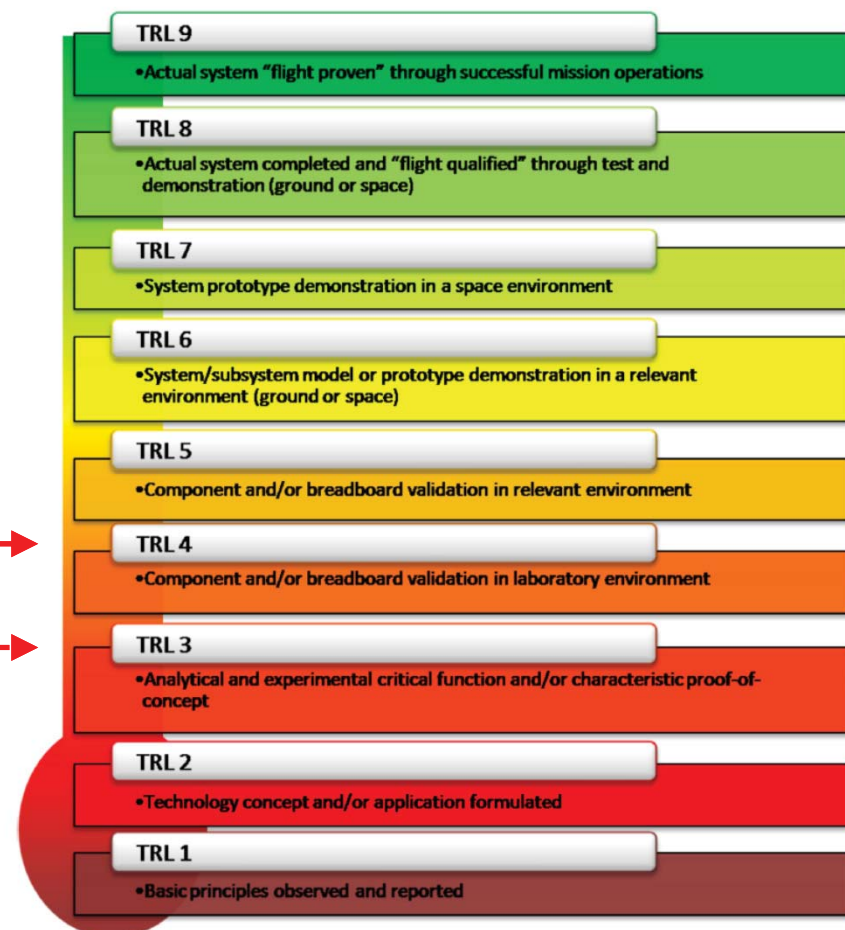


# Test results were used to assess maturity of fabrication methods

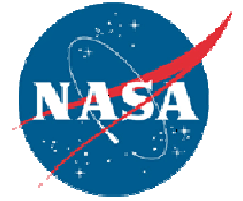
NASA *Technology Readiness Level* metric was used as a measure of the maturity of Additive Manufacturing processes

--- ready for engine test ---

- Fused Deposition Modeling for fabrication of Polymer Matrix Composites (TRL 4) --->
- Binder Jet process for fabrication of Ceramic Matrix Composites (TRL 3) --->



# Next Steps



## Optimize Processing & Improve Properties

- **Constituent Optimization:** utilize spherical shaped SiC powders for improved packing
- **Pursue Alternate Densification Approaches:** add carbon powder to powder bed for conversion to SiC during infiltration with molten silicon.
- **Fiber Coatings:** investigate the effect of fiber coatings for optimization of fiber/matrix bond strength
- **Reduce porosity** in polymers using higher temperature thermoplastic filaments (FDM) or thermoset polymers (Selective Laser Sintering)

## Thermomechanical Testing

- Optimize fiber volume fraction based on property measurements

## Turbine Engine Components

- Test components in relevant operating conditions to increase TRL